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POLYMERIC ANTIOXIDANTS

RELATED APPLICATION

This application is a continuation-in-part of U.S. Application No. 10/408,679, filed April 4, 2003, which claims the benefit of U.S. Provisional Application No. 60/370,468, filed on April 5, 2002. This application is also a continuation-in-part of International Application No. PCT/US03/10782, which designated the United States and was filed on April 4, 2003, published in English, which claims the benefit of U.S. Provisional Application No. 60/370,468, filed on April 5, 2002. The entire teachings of the above applications are incorporated herein by reference.

GOVERNMENT SUPPORT

The invention was supported, in whole or in part, by a grant DMR-9986644 from National Science Foundation. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

Synthetic antioxidant preservatives are added to a wide variety of products during processing and storage. The types of products include foods, plastics and packaging materials. When an oxidizing event takes place in a product, the antioxidant molecules rapidly react to form antioxidant radicals. This reaction protects the product from damage resulting from the oxidizing event and consequently increases the shelf life of the product. Common synthetic antioxidant preservatives include butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), *tert*-butylhydroquinone

(TBHQ), di-*tert*-butylhydroquinone (DTBHQ), and propyl gallate. There are also naturally occurring antioxidants, which include sesamol, sesamin, vitamin A and beta-carotene, vitamin E and tocopherols and vitamin C.

The use of antioxidant preservatives is particularly common in foods with significant unsaturated lipid content. These foods also contain quantities of unsaturated fatty acids. Unsaturation in fatty acids makes lipids susceptible to oxidation, which in turn leads to complex chemical changes in the lipids. These chemical changes eventually manifest themselves in the development of off-flavors (rancidity) in foods. The oxidation of unsaturated fatty acids is typically mediated by free radicals, which can be caused by heat, light, ionizing radiation, trace metals and some proteins. The use of antioxidant preservatives in lipid-containing foods minimizes rancidity, retards the formation of toxic oxidation products, allows maintenance of nutritional quality and increases the shelf life. The mechanism by which the antioxidant preservatives are believed to act involves scavenging peroxyl radicals and preventing propagation of the oxidation process. The antioxidant activity of these compounds is lost upon scavenging a free radical, so a food or other product is no longer protected from oxidation once all the antioxidant preservative has reacted with a free radical. In other words, the degree of protection from oxidation depends on the quantity of antioxidant preservative that is present.

Unfortunately, there are restrictions on the amount of synthetic antioxidant preservatives that can be added to a product, especially products intended for human or animal consumption. The U.S. Food and Drug Administration limits the amount of BHA, TBHQ and BHT in foods to 0.02% of total fat, because these compounds are suspected to be carcinogenic.

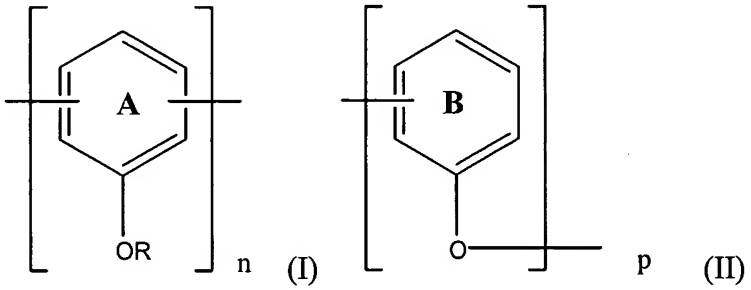
Consequently, there is a need for a new class of synthetic antioxidant preservatives that are less toxic to humans and animals. Also, it would be advantageous to develop an antioxidant preservative with increased potency and the ability to be readily processed with a variety of materials. Antioxidant preservatives with these improved properties would increase the shelf life and palatability of lipid-containing

food items, as well as other products containing moieties (e.g., unsaturated carbon-carbon bonds) that can be damaged by free radicals.

SUMMARY OF THE INVENTION

In one embodiment, the present invention includes a method of inhibiting oxidation of a substance, comprising the step of contacting the substance with a substituted benzene antioxidant polymer. Preferably, the substituted benzene antioxidant polymer includes one or more hydroxyl, acyl or ether moieties per benzene, particularly hydroxyl or ester moieties. In one example, every repeat unit of the antioxidant polymer is an antioxidant (e.g., a substituted benzene antioxidant). For purposes of the invention, a repeat unit having an antioxidant moiety is considered to be an antioxidant. In another example, the antioxidant polymer includes two or more polymerized substituted benzene monomers, where the polymerized substituted benzene monomers are directly connected by a C-C or C-O-C bond.

In a preferred embodiment, the antioxidant polymer comprises repeat units that include one or both of Structural Formulas (I) and (II):



where:

R is –H or a substituted or unsubstituted alkyl, acyl or aryl group;

Ring A is substituted with at least one *tert*-butyl group or substituted or unsubstituted n-alkoxycarbonyl group, and optionally one or more groups selected from the group consisting of -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, and a substituted or unsubstituted alkoxycarbonyl group;

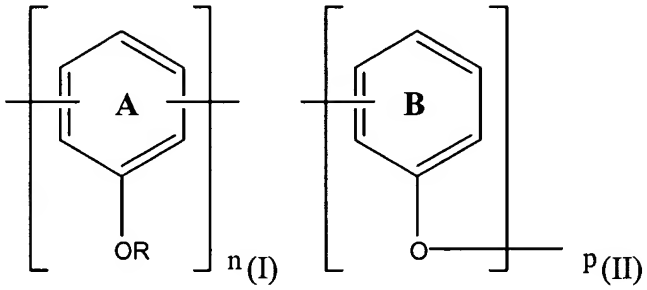
Ring B is substituted with at least one –H and at least one *tert*-butyl group or substituted or unsubstituted n-alkoxycarbonyl group and optionally one or more groups

selected from the group consisting of -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, and a substituted or unsubstituted alkoxycarbonyl group;

n is an integer equal to or greater than 2; and

p is an integer equal to or greater than 0.

In another preferred embodiment, the antioxidant polymer includes repeat units represented by one or both of Structural Formulas (I) and (II):



where:

R is –H or a substituted or unsubstituted alkyl, acyl or aryl group;

Ring A is substituted with at least one *tert*-butyl group, 1-ethenyl-2-carboxylic acid group or ester thereof, substituted or unsubstituted alkylenedioxy group, or substituted or unsubstituted n-alkoxycarbonyl group and zero, one or more additional functional groups;

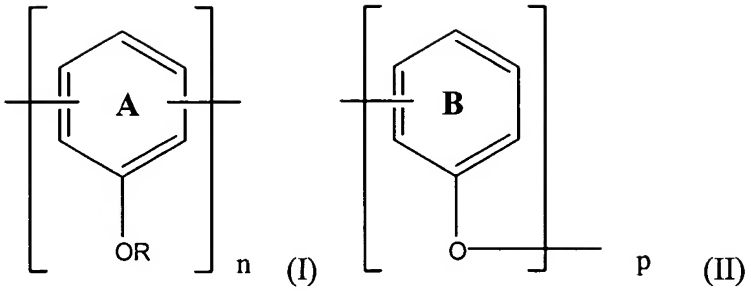
Ring B is substituted with at least one –H and at least one *tert*-butyl group, 1-ethenyl-2-carboxylic acid group or ester thereof, substituted or unsubstituted alkylenedioxy group, or substituted or unsubstituted n-alkoxycarbonyl group and zero, one or more additional functional groups;

n is an integer equal to or greater than 2; and

p is an integer equal to or greater than 0,

where the polymer includes two or more repeat units represented by one or both of Structural Formulas (I) and (II) that are directly connected by a C-C or C-O-C bond between benzene rings.

In another embodiment, the present invention includes an antioxidant polymer, comprising repeat units that include one or both of Structural Formulas (I) and (II):



where:

R is –H or a substituted or unsubstituted alkyl, acyl or aryl group;

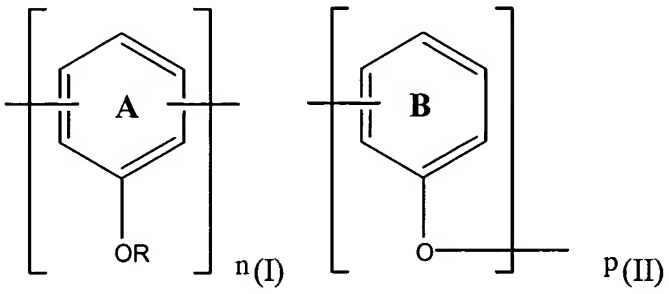
Ring A is substituted with at least one *tert*-butyl group or substituted or unsubstituted n-alkoxycarbonyl group, and optionally one or more groups selected from the group consisting of -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, and a substituted or unsubstituted alkoxycarbonyl group;

Ring B is substituted with at least one –H and at least one *tert*-butyl group or substituted or unsubstituted n-alkoxycarbonyl group and optionally one or more groups selected from the group consisting of -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, and a substituted or unsubstituted alkoxycarbonyl group;

n is an integer equal to or greater than 2; and

p is an integer equal to or greater than 0.

In yet another embodiment, the invention includes an antioxidant polymer having repeat units that include one or both of Structural Formulas (I) and (II):



where:

R is –H or a substituted or unsubstituted alkyl, acyl or aryl group;

Ring A is substituted with at least one *tert*-butyl group ortho to a hydroxyl or acyloxy group, 1-ethenyl-2-carboxylic acid group or ester thereof, substituted or

unsubstituted alkylenedioxy group, or substituted or unsubstituted n-alkoxycarbonyl group and zero, one or more additional functional groups;

Ring B is substituted with at least one –H and at least one *tert*-butyl group ortho to a hydroxyl or acyloxy group, 1-ethenyl-2-carboxylic acid group or ester thereof, substituted or unsubstituted alkylenedioxy group, or substituted or unsubstituted n-alkoxycarbonyl group and zero, one or more additional functional groups;

n is an integer equal to or greater than 2; and

p is an integer equal to or greater than 0,

where the polymer includes at least two repeat units represented by one or both of Structural Formulas (I) and (II) that are directly connected by a C-C or C-O-C bond, or where each repeat unit of the polymer is an antioxidant.

Polymers that do not include any repeat units represented by Structural Formula (I) are preferably substituted on Ring B with one or more hydroxyl or acyloxy groups.

The antioxidant polymers described herein can be part of a composition that includes other components. For example, one composition comprises an edible product and one or more of the antioxidant polymers described herein.

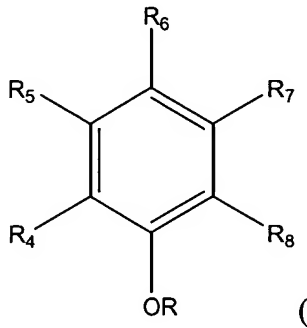
Another composition is used for packaging and comprises a packaging material and one or more of the antioxidant polymers described herein. Although its use is not limited to packaging materials, an example of such a composition includes polyethylene and poly(2-*tert*-butyl-4-hydroxyanisole).

Yet another composition of the invention comprises one or more of the antioxidant polymers described herein in combination with one or more synthetic and natural monomeric and oligomeric antioxidants and/or preservatives.

A further composition of the invention includes a cosmetic agent and one or more of the antioxidant polymers described herein.

The invention is also directed to a composition having a pharmaceutically active agent and one or more of the antioxidant polymers described herein.

The present invention also relates to a method of preparing an antioxidant polymer, which includes the step of polymerizing a monomer represented by Structural Formula (XIX):



(XIX),

where:

R is –H or a substituted or unsubstituted alkyl, acyl or aryl group; and

R_4, R_5, R_6, R_7 and R_8 are independently –H, -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, a substituted or unsubstituted alkoxycarbonyl group, a substituted or unsubstituted alkoxy group or a saturated or unsaturated carboxylic acid group; or

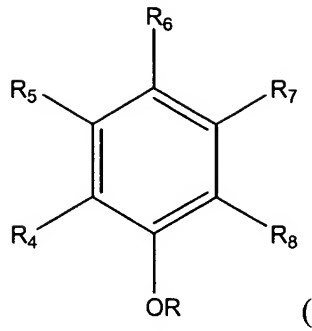
R_1, R_2, R_3, R_4 or R_5, in conjunction with an adjacent R_1, R_2, R_3, R_4 or R_5, forms a substituted or unsubstituted alkylenedioxy group;

provided that:

(1) at least one of R_4, R_5, R_7 and R_8 is a *tert*-butyl group, 1-ethenyl-2-carboxylic acid group or ester thereof, substituted or unsubstituted alkylenedioxy group, or substituted or unsubstituted n-alkoxycarbonyl group, and at least two of R_4, R_5, R_6, R_7 and R_8 are –H; or

(2) at least one of R_4, R_5, R_7 and R_8 is a *tert*-butyl group, 1-ethenyl-2-carboxylic acid group or ester thereof, substituted or unsubstituted alkylenedioxy group, or substituted or unsubstituted n-alkoxycarbonyl group, at least one of R_4, R_5, R_6, R_7 and R_8 is a hydroxyl, alkoxycarbonyl or aryloxycarbonyl group, and at least one of R_4, R_5, R_6, R_7 and R_8 is –H.

In a particular embodiment, the method of preparing an antioxidant polymer includes the step of polymerizing a monomer represented by Structural Formula (XIX):



(XIX),

where:

R is –H or a substituted or unsubstituted alkyl, acyl or aryl group; and

R_4, R_5, R_6, R_7 and R_8 are independently –H, -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, or a substituted or unsubstituted alkoxycarbonyl group,

provided that:

(1) at least one of R_4, R_5, R_6, R_7 and R_8 is a *tert*-butyl group or a substituted or unsubstituted alkoxycarbonyl group, and at least two of R_4, R_5, R_6, R_7 and R_8 are –H; or

(2) at least one of R_4, R_5, R_6, R_7 and R_8 is a *tert*-butyl group or a substituted or unsubstituted alkoxycarbonyl group, at least one of R_4, R_5, R_6, R_7 and R_8 is a hydroxyl, alkoxy, alkoxycarbonyl or aryloxycarbonyl group, and at least one of R_4, R_5, R_6, R_7 and R_8 is –H.

The polymerization can be catalyzed by an enzyme or an enzyme mimetic capable of polymerizing a substituted benzene compound in the presence of hydrogen peroxide. Alternatively, the polymerization is catalyzed by a non-enzymatic chemical method.

The invention also is directed to a method of preparing phenolic polymers that includes the steps of:

a) protecting at least one hydroxyl group of an substituted or unsubstituted phenol with a protecting group, thereby obtaining one or more protected hydroxyl groups; and

b) polymerizing the substituted or unsubstituted phenol,

thereby obtaining the phenolic polymer.

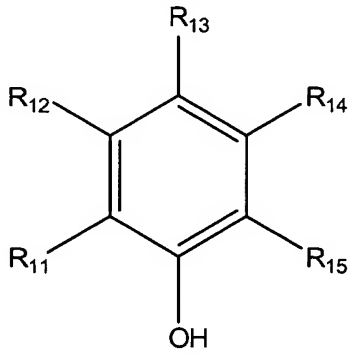
In one embodiment, the method of preparing a phenolic polymer includes the steps of:

a) protecting two hydroxyl groups of an substituted or unsubstituted hydroquinone with protecting groups, thereby forming protected hydroxyl groups; and

b) polymerizing the substituted or unsubstituted hydroquinone,

thereby obtaining the phenolic polymer.

In another embodiment, the method of preparing a phenolic polymer involves protecting with a protecting group at least one hydroxyl group of a monomer represented by Structural Formula (XXIX):



(XXIX),

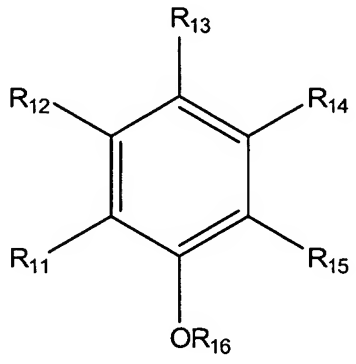
where:

R_{11}, R_{12}, R_{13}, R_{14} and R_{15} are independently –H, -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, a substituted or unsubstituted alkoxycarbonyl or aryloxycarbonyl group, a substituted or unsubstituted alkoxy group or a saturated or unsaturated carboxylic acid group; or

R_{11}, R_{12}, R_{13}, R_{14} or R_{15}, in conjunction with an adjacent R_{11}, R_{12}, R_{13}, R_{14} or R_{15}, forms a substituted or unsubstituted alkylenedioxy group;

provided that at least one of R_{11}, R_{12}, R_{13}, R_{14} and R_{15} is a *tert*-butyl group, 1-ethenyl-2-carboxylic acid or ester thereof, a substituted or unsubstituted alkylenedioxy group or a substituted or unsubstituted n-alkoxycarbonyl group, at least one of R_{11}, R_{12}, R_{13}, R_{14} and R_{15} is a hydroxyl group, and at least one of R_{11}, R_{12}, R_{13}, R_{14} and R_{15} is –H; and polymerizing the monomer, thereby forming a phenolic polymer.

In yet another embodiment, the method of preparing a phenolic polymer involves polymerizing a monomer represented by Structural Formula (XXX):



(XXX),

where:

R_{16} is a protecting group; and

R_{11}, R_{12}, R_{13}, R_{14} and R_{15} are independently –H, -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, a substituted or unsubstituted alkoxycarbonyl or aryloxycarbonyl group, a substituted or unsubstituted alkoxy group or a saturated or unsaturated carboxylic acid group; or

R_{11}, R_{12}, R_{13}, R_{14} or R_{15}, in conjuction with an adjacent R_{11}, R_{12}, R_{13}, R_{14} or R_{15}, forms a substituted or unsubstituted alkylenedioxy group,

thereby forming a phenolic polymer; and removing the protecting group.

In another aspect, the invention relates to a phenolic polymer, where the polymer includes substituted or unsubstituted phenol repeat units directly connected by C-C or C-O-C bonds, provided that at least 90% of the repeat units in the polymer are directed connected by C-C bonds.

One advantage of antioxidant polymers of the present invention is that they are expected to be less toxic or even non-toxic to animals, by virtue of being largely unabsorbed. Also, these polymers are generally more potent and exhibit greater thermal stability than small molecule antioxidants, so that a smaller quantity of antioxidant is typically needed to achieve the same protective effect. In addition, the antioxidant polymers can be blended into another polymeric material or can form a thin film coating on the material, and unlike a small molecule antioxidant, diffusion out of the polymeric

material will most often occur slowly. The invention also provides a largely environmentally-safe method for preparing these antioxidant polymers.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a high resolution 500 MHz ^{1}H NMR spectrum of 2-*tert*-butyl-4-hydroxyanisole (2-BHA).

Fig. 2 shows a high resolution 500 MHz ^{1}H NMR spectrum of enzymatically polymerized poly(2-BHA).

Fig. 3 shows the matrix assisted laser desorption ionization time-of-flight mass spectrum (MALDI-TOF-MS) of the poly(2-BHA), which indicates that a distribution of polymeric species were formed.

Fig. 4 shows the comparative thermogravimetric analysis of 2-BHA and poly(2-BHA).

Fig. 5 shows the matrix assisted laser desorption ionization time-of-flight mass spectrum (MALDI-TOF-MS) of the poly(*tert*-butyl-hydroquinone) (poly(TBHQ)), which indicates that a distribution of polymeric species were formed.

Fig. 6 shows the antioxidant activity profile of 2-BHA and poly(2-BHA)at 100 ppm in the beta-carotene/linoleate model system described in Example 2.

Fig. 7 shows high resolution 500 NMR ^{1}H NMR spectra of (a) 2-*tert*-butylhydroquinone (TBHQ), (b) the diacetate of TBHQ, (c) the monoacetate of TBHQ, (d) the poly(monoacetate of TBHQ) and (e) poly(TBHQ).

DETAILED DESCRIPTION OF THE INVENTION

The present invention is generally directed to a method of inhibiting the oxidation of a substance, which involves contacting the substance with a substituted benzene antioxidant polymer. The invention is also directed to the substituted benzene antioxidant polymers, various compositions containing such antioxidant polymers, and methods of preparing such antioxidant polymers.

For purposes of the present invention, a "method of inhibiting oxidation" is defined herein as a method that inhibits the propagation of a free radical-mediated

process. Free radicals can be generated by heat, light, ionizing radiation, metal ions and some proteins and enzymes. Inhibiting oxidation also includes inhibiting reactions caused by the presence of oxygen, ozone or another compound capable of generating these gases or reactive equivalents of these gases.

Repeat units of the antioxidant polymers of the invention include substituted benzene molecules. These benzene molecules are typically based on phenol or a phenol derivative, such that they have at least one hydroxyl, ester or ether functional group. Preferably, the benzene molecules have a hydroxyl group. The hydroxyl group is not restricted to being a free hydroxyl group, and the hydroxyl group can be protected or have a cleavable group attached to it (e.g., an ester group). Such cleavable groups can be released under certain conditions (e.g., changes in pH), with a desired shelf life or with a time-controlled release (e.g., measured by the half-life), which allows one to control where and/or when an antioxidant polymer is able to exert its antioxidant effect.

Substituted benzene repeat units of an antioxidant polymer of the invention are also typically substituted with a bulky alkyl group, a 1-ethenyl-2-carboxylic acid group, a substituted or unsubstituted alkylenedioxy group, or an n-alkoxycarbonyl group. Preferably, the benzene monomers are substituted with a bulky alkyl group. More preferably, the bulky alkyl group is located *ortho* or *meta* to a hydroxyl group on the benzene ring. A "bulky alkyl group" is defined herein as an alkyl group that is branched *alpha-* or *beta-* to the benzene ring. Preferably, the alkyl group is branched alpha to the benzene ring. More preferably, the alkyl group is branched twice alpha to the benzene ring (i.e., to form an alpha-tertiary carbon), such as in a *tert*-butyl group. Other examples of bulky alkyl groups include isopropyl, 2-butyl, 3-pentyl, 1,1-dimethylpropyl, 1-ethyl-1-methylpropyl and 1,1-diethylpropyl. The bulky alkyl groups are preferably unsubstituted, but they can be substituted with a functional group that does not interfere with the antioxidant activity of the molecule or the polymer.

Substituted benzene repeat units that are substituted with a substituted or unsubstituted alkylenedioxy group typically have an unsubstituted alkylenedioxy group. Substituted alkylenedioxy groups are also suitable, although the substituents should not

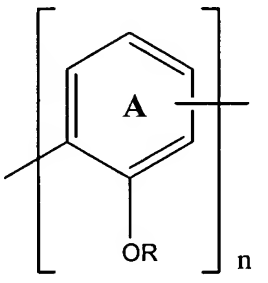
interfere with the antioxidant activity of the molecule or the polymer. Typically, an alkylenedioxy group is a lower alkylenedioxy group, such as a methylenedioxy group or an ethylenedioxy group. A methylenedioxy group is preferred (as in sesamol).

Straight chained alkoxycarbonyl groups typically have an alkyl chain of one to sixteen carbon atoms, and include methoxycarbonyl, ethoxycarbonyl, n-propoxycarbonyl, n-butoxycarbonyl and n-pentoxycarbonyl. n-propoxycarbonyl is a preferred group. Similar to the bulky alkyl groups, n-alkoxycarbonyl groups are optionally substituted with a functional group that does not interfere with the antioxidant activity of the molecule or the polymer. Alkoxycarbonyl groups can also be present in their hydrolyzed form, namely as carboxy groups or carboxylic acid groups.

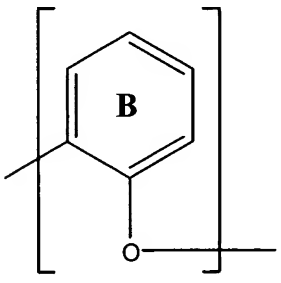
In substituted benzene repeat units having a 1-ethenyl-2-carboxylic acid group or an ester thereof, the 1-carbon (i.e., the carbon distal from the carboxylic acid moiety) is attached to the benzene ring.

In addition to the substituents named above, substituted benzene repeat units can have additional functional groups as substituents. For example, the additional functional groups can be selected from the group consisting of -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, a substituted or unsubstituted alkoxycarbonyl group, a substituted or unsubstituted alkoxy group and a saturated or unsaturated carboxylic acid group. Typically, the additional functional groups are selected from the group consisting of –OH, a substituted or unsubstituted alkoxy group and a saturated or unsaturated carboxylic acid group.

Preferred polymers of the present invention include repeat units represented by one or both of Structural Formulas (III) and (IV):



(III)

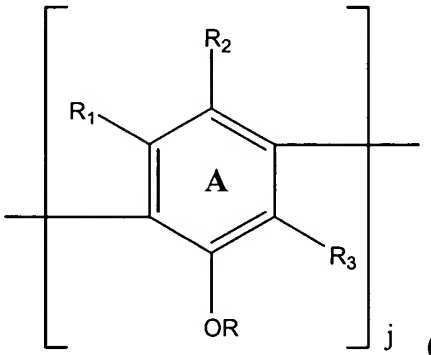


(IV),

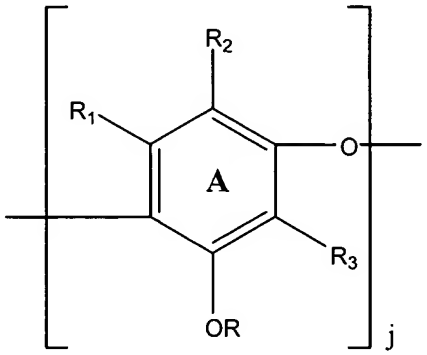
where Rings A and B are substituted as described above and n and p are as defined above.

Preferably, Ring A and Ring B in Structural Formulas (I) to (IV) are each substituted with at least one *tert*-butyl group.

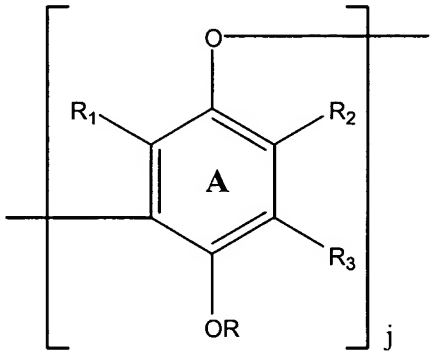
The polymer advantageously includes repeat units represented by one or more of Structural Formulas (Va), (Vb), (Vc), (VIa), (VIb) and (VIc):



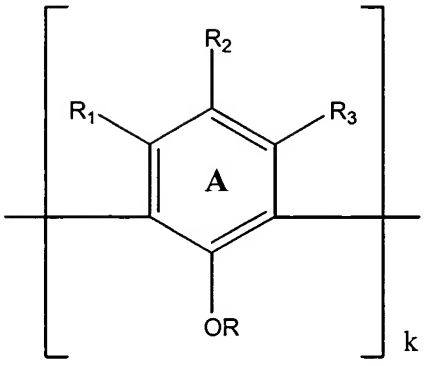
(Va)



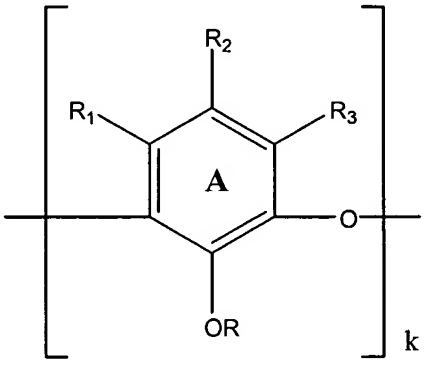
(Vb)



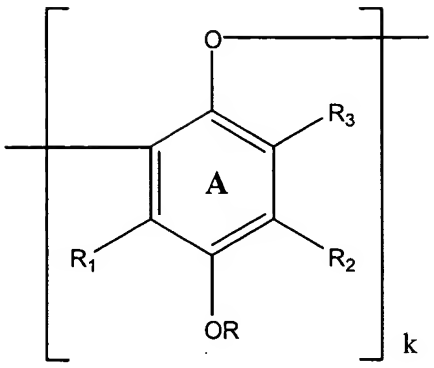
(Vc)



(VIa)



(VIb)

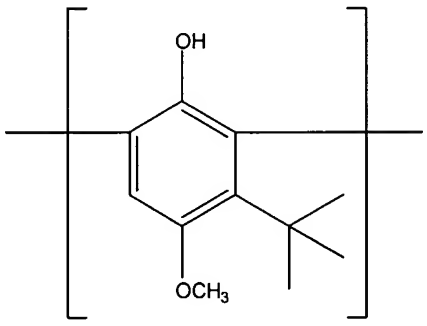


(VIc),

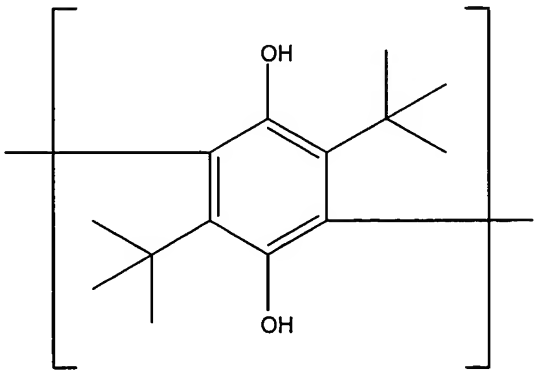
where R_1, R_2 and R_3 are independently selected from the group consisting of –H, -OH, -NH, -SH, a substituted or unsubstituted alkyl or aryl group, and a substituted or unsubstituted alkoxycarbonyl group, provided that at least one of R_1, R_2 and R_3 is a *tert*-butyl group; and j and k are independently integers of zero or greater, such that the sum of j and k is equal to or greater than 2.

In a preferred embodiment, R is –H or $–CH_3$; R_2 is –H, -OH, or a substituted or unsubstituted alkyl group; or both.

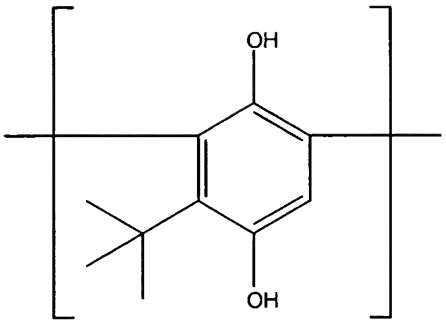
Specific examples of repeat units included in polymers of the present invention are represented by one of the following structural formulas:



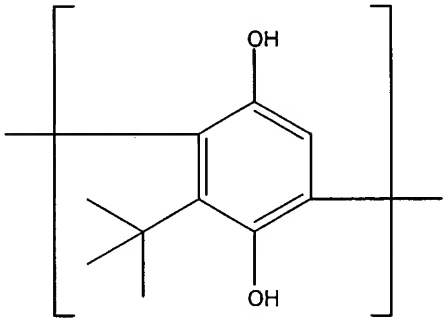
(VII),



(VIII),



(IX),



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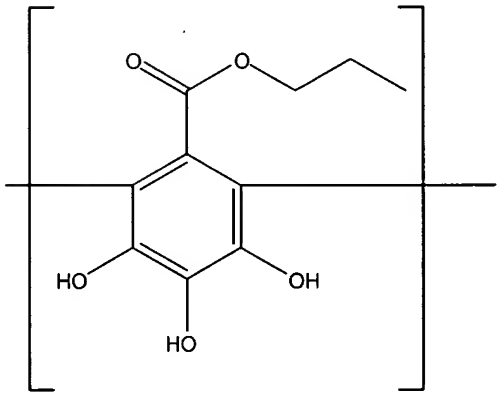
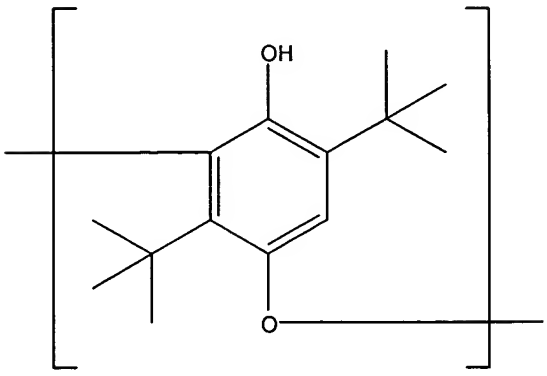
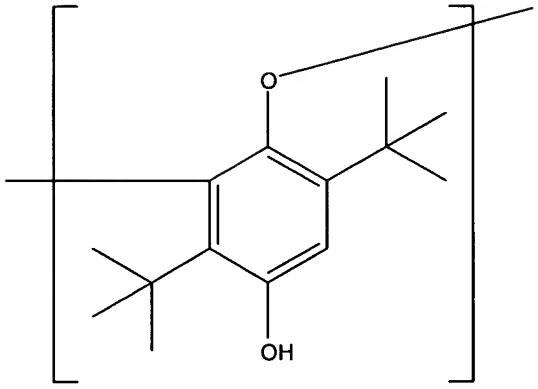


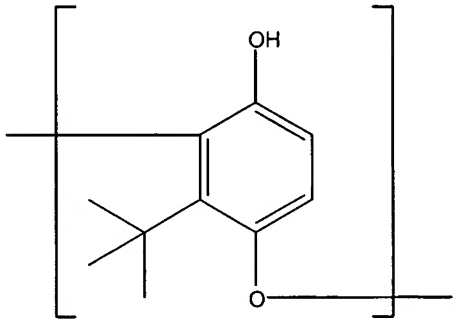
(XI),



(XII),



(XIII)



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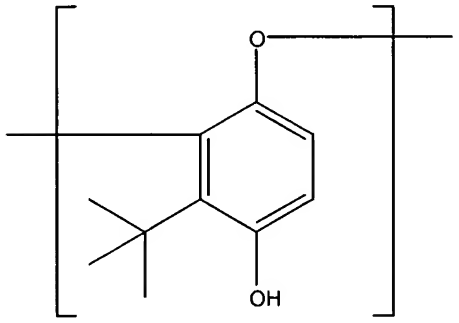

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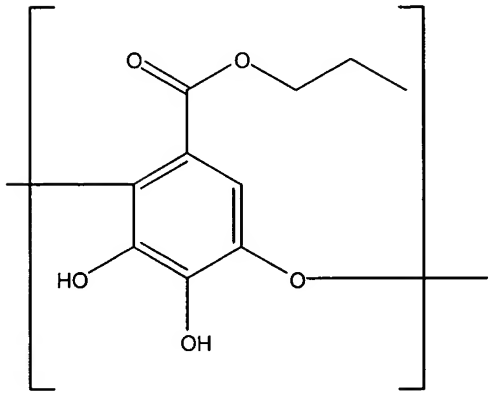

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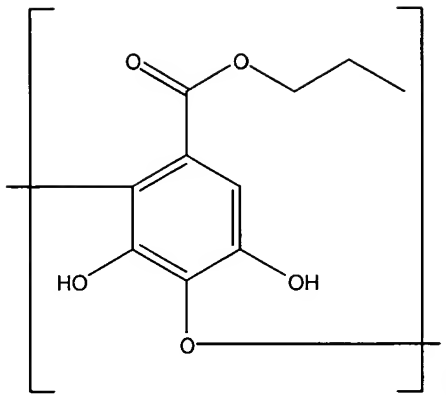
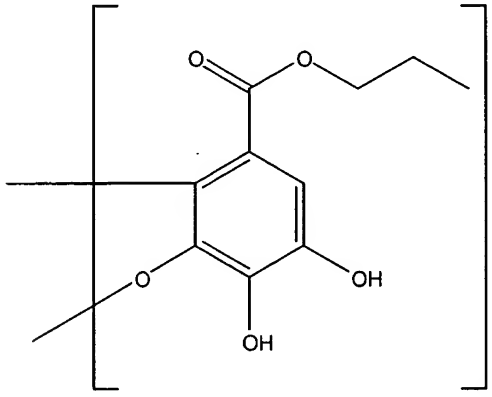
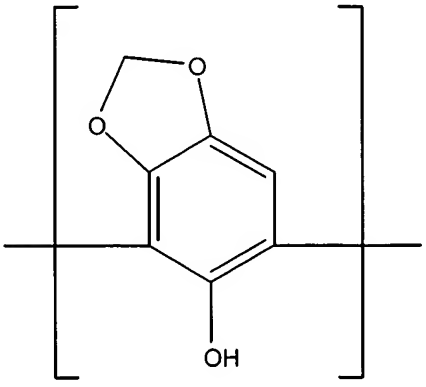


(XVII),



(XVIII),



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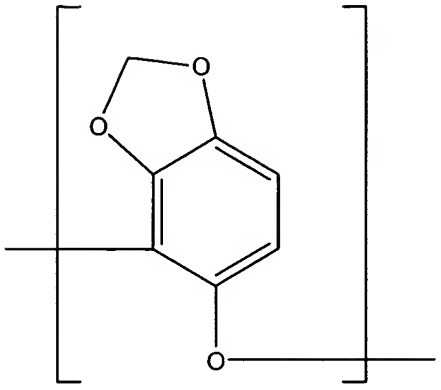

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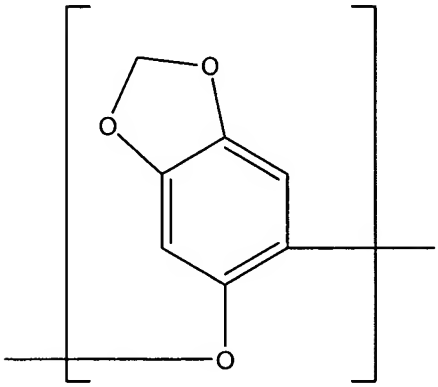


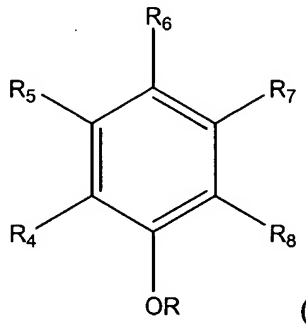
(XVIIIc).

Advantageously, a polymer of the present invention consists of repeat units represented by one or more of Structural Formulas (VII) to (XVIIIc).

Although Structural Formulas (XI), (XVI), (XVII) and (XVIII) are represented as having a propoxycarbonyl substituent, this group can generally be replaced with a different C_1-C_{16} n-alkoxycarbonyl group or can be a carboxylate group.

A preferred polymer is poly(2-*tert*-butyl-4-hydroxyanisole).

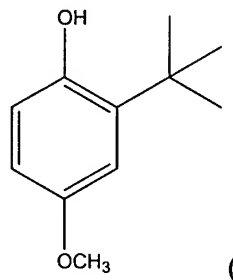
Antioxidant polymers of the present invention can be prepared by polymerizing a molecule represented by Structural Formula (XIX):



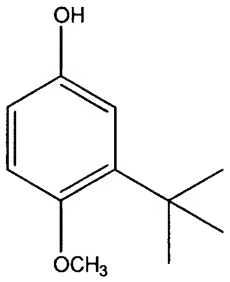
(XIX).

Preferably, a molecule represented by Structural Formula (XIX) has one, two, three, four or five of the following features. In the first feature, at least one of R_5, R_7 and R_8 is a *tert*-butyl group. In the second feature, R_4 is –H. In the third feature, one or both of R_7 and R_8 is –H. In the fourth feature, R is –H or $-CH_3$. In the fifth feature, R_6 is –H, -OH or a substituted or unsubstituted alkyl group. More preferably, a molecule represented by Structural Formula (XIX) has the first and second features; the first, second and third features; the first, second, third and fourth features; or the first, second, third, fourth and fifth features.

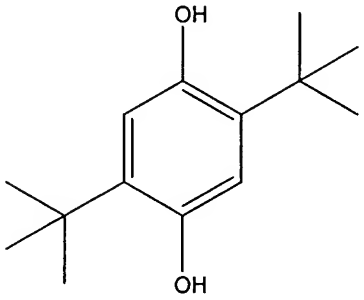
Specific examples of monomers that can be polymerized to form an antioxidant polymer of the present invention are represented by one of the following structural formulas:



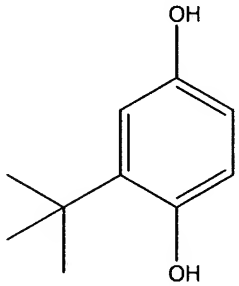
(XX),



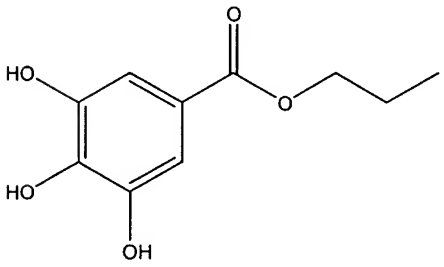
(XXI),



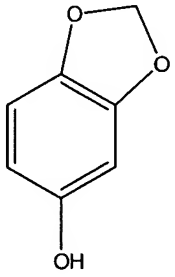
(XXIII),



(XXIV)



(XXV) and



(XXVa).

The propoxycarbonyl group in Structural Formula (XXV) can alternatively be an alkoxycarbonyl group, such as where the alkoxy moiety has from one to sixteen carbon atoms.

Antioxidant polymers of the present invention have two or more repeat units, preferably greater than about five repeat units. The molecular weight of the polymers disclosed herein is generally selected to be appropriate for the desired application. Typically, the molecular weight is greater than about 500 atomic mass units (amu) and less than about 2,000,000 amu, greater than about 1000 amu and less than about 100,000, greater than about 2,000 amu and less than about 10,000 amu, or greater than about 2,000 amu and less than about 5,000 amu. For food or edible products (e.g., products fit for human consumption), the molecular weight is advantageously selected to be large enough so that an antioxidant polymer cannot be absorbed by the gastrointestinal tract, such as greater than 1000 amu. For antioxidant polymers blended with a polymeric material, the molecule weight is advantageously selected such that the rate of diffusion of the antioxidant polymer through the polymeric material is slow relative to the expected lifetime of the polymeric material.

Antioxidant polymers of the present invention can be either homopolymers or copolymers. A copolymer preferably contains two or more or three or more different repeating monomer units, each of which has varying or identical antioxidant properties (including monomers having no antioxidant activity). The identity of the repeat units in a copolymer can be chosen to modify the antioxidant properties of the polymer as a whole, thereby giving a polymer with tunable properties. The second, third and/or further repeat units in a copolymer can be either a synthetic or natural antioxidant. In one example, a composition of the invention includes one or more homopolymers and one or more copolymers (e.g., in a blend). Preferably, both homopolymers and copolymers include two or more substituted benzene repeat units that are directly connected by a C-C or C-O-C bond. Preferably, at least 50%, such as at least 70%, for example, at least 80%, but preferably about 100% of the repeat units in a copolymer are substituted benzene repeat units directly connected by a C-C or C-O-C bond.

Examples of copolymers include poly(TBHQ-*co*-propyl gallate), poly(TBHQ-*co*-BHA), poly(TBHQ-*co*-sesamol), poly(BHA-*co*-sesamol), poly(propyl gallate-*co*-sesamol) and poly(BHA-*co*-propyl gallate). The ratio of one monomer to another, on a molar basis, is typically about 100:1 to about 1:100, such as about 10:1 to about 1:10, for example, about 2:1 to about 1:2. In one example, the ratio of monomers is about 1:1.

Antioxidant polymers of the present invention are typically insoluble in aqueous media, although certain polymers of gallic acid and its esters are water soluble. The solubility of the antioxidant polymers in non-aqueous media (e.g., oils) depends upon the molecular weight of the polymer, such that high molecular weight polymers are typically sparingly soluble in non-aqueous media. When an antioxidant polymer of the invention is insoluble in a particular medium or substrate, it is preferably well-mixed with that medium or substrate.

Antioxidant polymers of the present invention can be branched or linear, but are preferably linear. Branched antioxidant polymers can only be formed from benzene molecules having three or fewer substituents (e.g., three or more hydrogen atoms), as in Structural Formulas (XX), (XXI) and (XXIV).

Polymerization of the monomers can be catalyzed by a natural or synthetic enzyme or an enzyme mimetic capable of polymerizing a substituted benzene compound in the presence of hydrogen peroxide, where the enzyme or enzyme mimetic typically has a heme or related group at the active site. One general class of enzymes capable of catalyzing this reaction is commonly referred to as the peroxidases. Horseradish peroxidase, soybean peroxidase, *Coprinus cinereus* peroxidase, and *Arthromyces ramosus* peroxidase are readily available peroxidases. Other enzymes capable of catalyzing the reaction include laccase, tyrosinase, and lipase. Suitable enzymes are able to catalyze the formation of a carbon-carbon bond and/or a carbon-oxygen-carbon bond between two aryl (e.g., phenol) groups when a peroxide (e.g., hydrogen peroxide or an organic peroxide) is present. A subunit or other portion of a peroxidase is acceptable, provided that the active site of the enzyme is still functional.

Enzyme mimetics typically correspond to a part of an enzyme, so that they can carry out the same reaction as the parent enzyme but are generally smaller than the parent enzyme. Also, enzyme mimetics can be designed to be more robust than the parent enzyme, such as to be functional under a wider variety of conditions (e.g., different pH range and/or aqueous, partially aqueous and non-aqueous solvents) and are generally less subject to degradation or inactivation. Suitable enzyme mimetics include hematin, tyrosinase-model complexes and metal-salen (e.g., iron-salen) complexes. Hematin, in particular, can be functionalized to allow it to be soluble under a wider variety of conditions is disclosed in U.S. Application No. 09/994,998, filed November 27, 2001, the contents of which are incorporated herein by reference.

The enzymes and enzyme mimetics described above can be immobilized on a solid. In addition, the enzymes and enzyme mimetics can be dispersed in a solution or suspension.

The monomers described herein can also be polymerized by non-enzymatic chemical methods. For example, polymerization can be catalyzed by metal compounds such as iron chloride or a metallocene. Also, polymerization can be catalyzed by cationic, anionic or free radical initiators such as N,N-azobisisobutyronitrile (AIBN), acetylacetone and peroxides (e.g., *tert*-butyl hydroxide, benzyl peroxide).

Polymerizations of the present invention can be carried out under a wide variety of conditions. The pH is often between about pH 1.0 and about pH 12.0, typically between about pH 6.0 and about pH 11.0. The temperature is generally above about 0°C, such as between about 0°C and about 45°C or between about 15°C and about 30°C (e.g., room temperature). The solvent can be aqueous (preferably buffered), organic, or a combination thereof. Organic solvents are typically polar solvents such as ethanol, methanol, isopropanol, dimethylformamide (DMF), dioxane, acetonitrile, dimethylsulfoxide (DMSO) and tetrahydrofuran (THF). The concentration of monomer or comonomers is typically 0.001 M or greater. Also, the concentration of buffer is typically 0.001 M or greater.

Polymerizations of the invention using a catalytic amount of one of the enzymes or enzyme mimetics described above typically use between about one unit/mL and five units/mL, where one unit will form 1.0 mg purpurogallin from pyrogallol in 20 seconds at pH 6.0 at 20°C. Preferably, the enzyme or enzyme mimetic is added to the solution after addition of the antioxidant monomer or comonomers. A peroxide is then added incrementally to the reaction mixture, such as not to de-activate the enzyme or enzyme mimetic, until an amount approximately stoichiometric with the amount of antioxidant monomer or comonomers has been added.

Although the enzyme or enzyme mimetic or the chemical initiator is responsible for formation of phenol-based free radicals needed for chain propagation, the coupling of radicals to form a polymer chain is controlled by the phenoxy radical and solvent chemistries. Further details regarding the coupling of phenoxy radicals can be found in "Enzymatic catalysis in monophasic organic solvents," Dordick, J.S., *Enzyme Microb. Technol.* 11:194-211 (1989), the contents of which are incorporated herein by reference. Coupling between substituted benzene monomers typically occurs ortho and/or para to a hydroxyl group. Coupling rarely occurs meta to a hydroxyl group.

Polymerization preferably results in the formation of C-C bonds between substituted benzene repeat units (i.e., the benzene rings are directly attached to each other in a chain). Preferred polymers will contain at least about 99% C-C bonds, at least about 98% C-C bonds, at least about 95% C-C bonds, at least about 90% C-C bonds, at least about 80% C-C bonds, at least about 70% C-C bonds, at least about 60% C-C bonds or at least about 50% C-C bonds. Especially preferred polymers contain about 100% C-C bonds.

More generally, the invention also includes a method for polymerizing phenolic compounds that increases the number of C-C bonds formed during polymerization and decreases the extent of C-O-C bonding, thereby resulting in the amount of C-C coupling described immediately above. This preparation method is not limited to phenolic antioxidants.

In one embodiment, the method involves protecting at least one hydroxyl group of a substituted or unsubstituted phenol with a protecting group to obtain protected hydroxyl groups and then polymerizing the phenol to obtain a phenolic polymer. The phenol should have at least one additional hydroxyl substituent, such that there are two or more hydroxyl groups attached to the ring, at least one of which is a free hydroxyl group for polymerization. The phenol can be an antioxidant. Suitable types of protected hydroxyl groups include ether, ester, silyl ether, carbonate, phosphinate, carbamate, sulfonate, nitrate, phosphoramidate, borate ester, phosphinothioyl ester and sulfenate functional groups. The protecting groups are independently chosen and need not be the same for each hydroxyl group. Typically, a hydroxyl group is protected as an ether or an ester functional group, more typically an ester (i.e., where the protecting group is an acyl group). When the hydroxyl group is protected as an ester, a common protecting group is an acetyl group. When the hydroxyl group is protected as an ether, a common protecting group is a long chain alkyl group (e.g., having more than 12 carbon atoms, such as 12-24 carbon atoms).

Substituted and unsubstituted phenols having two or more total hydroxyl groups (e.g., hydroquinones), where two or more of the hydroxyl groups are protected, advantageously undergo a partial deprotection step prior to polymerization. This deprotection step is intended to leave at least one hydroxyl group protected and to result in at least one free hydroxyl group. In a hydroquinone, for example, one hydroxyl group will be protected and the other hydroxyl group will be deprotected. For hydroquinones substituted with a bulky alkyl group (e.g., a *tert*-butyl group), one hydroxyl group is considered to be proximal to the alkyl group and the other hydroxyl group is considered to be distal to the alkyl group. Preferably, the hydroxyl group distal to the bulky alkyl group is deprotected prior to polymerization.

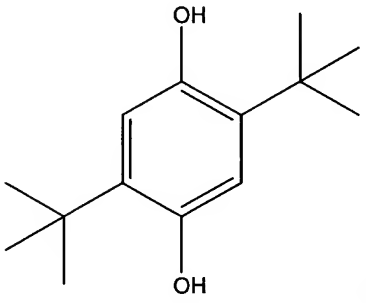
Deprotection is generally performed using a selective deprotection method, so that at least one of the hydroxyl group in a phenol remains protected. Enzymatic deprotection, such as with lipase, is an effective means of selective deprotection.

Once one or more hydroxyl groups have been protected, the phenol is polymerized. The polymerization method is generally not critical. Suitable polymerization catalysts are as described above and include enzymes and enzyme mimetics (e.g., peroxidase, laccase, tyrosinase, lipase, hematin, tyrosinase-model complexes and metal-salen complexes such as iron-salen complexes). Chemical reagents, as described above, and light are also suitable catalysts.

After polymerization, all or a portion of the protecting groups on the phenolic polymer can be removed.

The phenolic polymer resulting from this method can be used in a variety of applications. These phenolic polymers can have antioxidant properties and/or electrical conductivity. The polymers can also be useful in optoelectronic applications.

When a monomer represented by Structural Formula (XXIX) is polymerized by this method, one or more of R_{12}, R_{14} and R_{15} are preferably a *tert*-butyl group. Also, R_{11} is preferably –H. Even more preferably, R_{12} is a *tert*-butyl group and R_{11}, R_{14} and R_{15} are each –H. Other representative monomers encompassed by Structural Formula (XXIX) include the following:



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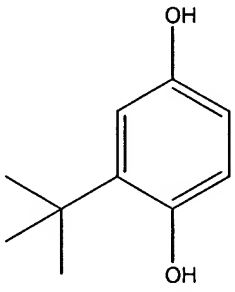

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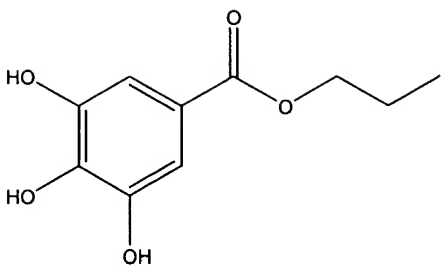
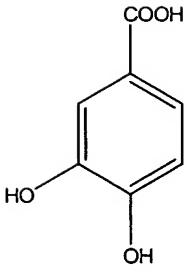
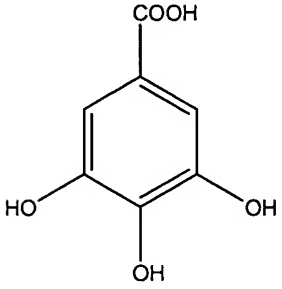


(XXVI),



(XXVII) and



(XXVIII).

In another aspect, one of R_{11}, R_{12}, R_{13}, R_{14} and R_{15} is –OH and both hydroxyl groups are protected by protecting groups. One protected hydroxyl group is considered to be distal to the *tert*-butyl group, 1-ethenyl-2-carboxylic acid or ester thereof, substituted or unsubstituted alkylene dioxy group or substituted or unsubstituted n-alkoxycarbonyl group and the other protected hydroxyl group is considered to be proximal to the *tert*-butyl group, 1-ethenyl-2-carboxylic acid or ester thereof, substituted or unsubstituted alkylene dioxy groupr unsubstituted n-alkoxycarbonyl group. Preferably, the distal protected hydroxyl group is deprotected prior to polymerization, particularly by an enzyme such as lipase. Chemical deprotection of the hydroxyl group is also suitable. The protecting groups are the same as described above. Also, the method of polymerizing the monomers represented by Structural Formula (XXIX) is the same as described above.

Polymers prepared by this method involving protecting hydroxyl groups typically have a molecular weight from about 500 amu to about 1,000,000 amu, such as about 1,000 amu to about 5,000 amu.

Antioxidant polymers of the present invention can be present in a wide variety of compositions where free radical mediated oxidation leads to deterioration of the quality of the composition, including edible products such as oils, foods (e.g., meat

products, dairy products, cereals, beverages, crackers, potato flakes, bakery products and mixes, dessert mixes, nuts, candies, etc.), and other products containing fats or other compounds subject to oxidation (e.g., chewing gum, flavorings, yeast, etc.).

Antioxidant polymers can also be present in plastics and other polymers, elastomers (e.g., natural or synthetic rubber), petroleum products (e.g., mineral oil, fossil fuels such as gasoline, kerosene, diesel oil, heating oil, propane, jet fuel), adhesives, lubricants, paints, pigments or other colored items, soaps and cosmetics (e.g., creams, lotions, hair products). Soaps and cosmetics, in particular, benefit from the addition of a large proportion of one or more antioxidant polymers of the invention. Soaps and cosmetics can contain, for example, about 1% to about 20% (e.g., about 5% to about 15%) by weight of antioxidant polymer.

The antioxidant polymers can be used to coat a metal as a rust and corrosion inhibitor.

Antioxidant polymers additionally can protect antioxidant vitamins (Vitamin A, Vitamin C, Vitamin E) and pharmaceutical products (i.e., those containing a pharmaceutically active agent) from degradation. The addition of antioxidant polymers is particularly advantageous when the vitamin or pharmaceutically active agent is present in a liquid composition, although the antioxidant polymers is expected also to have a benefit in solid compositions.

In food products, the antioxidant polymers will prevent rancidity. In plastics, the antioxidant polymers will prevent the plastic from becoming brittle and cracking.

Antioxidant polymers of the present invention can be added to oils to prolong their shelf life and properties. These oils can be formulated as vegetable shortening or margarine. Oils generally come from plant sources and include cottonseed oil, linseed oil, olive oil, palm oil, corn oil, peanut oil, soybean oil, castor oil, coconut oil, safflower oil, sunflower oil, canola (rapeseed) oil and sesame oil. These oils contain one or more unsaturated fatty acids such as caproleic acid, palmitoleic acid, oleic acid, vaccenic acid, elaidic acid, brassidic acid, erucic acid, nervonic acid, linoleic acid, eleosteric acid, alpha-linolenic acid, gamma-linolenic acid, and arachidonic acid, or partially

hydrogenated or trans-hydrogenated variants thereof. Antioxidant polymers of the present invention are also advantageously added to food or other consumable products containing one or more of these fatty acids.

The shelf life of many materials and substances contained within the materials, such as packaging materials, are enhanced by the presence of an antioxidant polymer of the present invention. The addition of an antioxidant polymer to a packaging material is believed to provide additional protection to the product contained inside the package. In addition, the properties of many packaging materials themselves, particularly polymers, are enhanced by the presence of an antioxidant regardless of the application (i.e., not limited to use in packaging). Common examples of packaging materials include paper, cardboard and various plastics and polymers. A packaging material can be coated with an antioxidant polymer (e.g., by spraying the antioxidant polymer or by applying as a thin film coating), blended with or mixed with an antioxidant polymer (particularly for polymers), or otherwise have an antioxidant polymer present within it. In one example, a thermoplastic polymer such as polyethylene, polypropylene or polystyrene is melted in the presence of an antioxidant polymer in order to minimize its degradation during the polymer processing. An antioxidant polymer can also be co-extruded with a polymeric material.

One example of a packaging material included in the present invention is commonly referred to as "smart packaging". Smart packaging is designed, for example, such that it controls gas exchange through the packaging. Examples of smart packaging are described in U.S. Patent Nos. 5,911,937, 5,320,889 and 4,977,004, the contents of which are incorporated herein in their entirety. One conventional type of smart packaging involves a layer of an oxygen barrier such as nylon or poly(ethylene-*co*-vinyl alcohol) that is typically sandwiched between one or more layers of a moisture-resistant polymer or polymer blend such as polyethylene terephthalate, poly(vinylidene chloride), poly(vinyl chloride), poly(ethylene) or poly(propylene). The layers of moisture-resistant polymer can be either the same or different. In the present invention,

one or more of the antioxidant polymers described herein can be added as an additional layer or can be blended with a layer of the packaging material.

One example of a composition that is particularly suitable as a packaging material includes polyethylene and poly(2-*tert*-butyl-4-hydroxyanisole), typically where the two polymers are blended together. The proportion of poly(2-*tert*-butyl-4-hydroxyanisole) in the composition is typically about 1 ppm to about 1,000 ppm, such as about 10 ppm to about 100 ppm. The composition can be, for example, in the form of a film or a pellet. The composition can also include a monomeric antioxidant, such as 2-*tert*-butyl-4-hydroxyanisole. When the monomeric antioxidant is present, the concentration is typically about 1 ppm to about 1,000 ppm.

The concept of having a mixture of an antioxidant polymer and another antioxidant or polymer can generally be applied to combinations of one or more antioxidant polymers described herein and one or more synthetic and/or natural monomeric and/or oligomeric antioxidants and/or preservatives. Such compositions are expected to have both short-term and long-term antioxidant activity. The ratio of polymer to monomer and/or oligomer in a composition can be selected so that the composition has the desired set of properties. For example, the ratio of polymer to monomer and/or oligomer can be about 1:100 to about 100:1, such as about 1:10 to about 10:1. Typically, the absolute concentration of antioxidant polymers in such compositions ranges from about 0.1 ppm to about 10,000 ppm.

An alkyl group is a saturated hydrocarbon in a molecule that is bonded to one other group in the molecule through a single covalent bond from one of its carbon atoms. Examples of lower alkyl groups include methyl, ethyl, *n*-propyl, *iso*-propyl, *n*-butyl, *sec*-butyl and *tert*-butyl. An acyl group is a substituted or unsubstituted alkyl group that contains a terminal carbonyl moiety.

Aryl groups include carbocyclic aryl groups such as phenyl, 1-naphthyl, 2-naphthyl, 1-anthracyl and 2-anthracyl, and heterocyclic aryl groups such as *N*-imidazolyl, 2-imidazole, 2-thienyl, 3-thienyl, 2-furanyl, 3-furanyl, 2-pyridyl, 3-pyridyl, 4-pyridyl, 2-pyrimidyl, 4-pyrimidyl, 2-pyranyl, 3-pyranyl, 3-pyrazolyl, 4-pyrazolyl, 5-

pyrazolyl, 2-pyrazinyl, 2-thiazole, 4-thiazole, 5-thiazole, 2-oxazolyl, 4-oxazolyl and 5-oxazolyl.

Aryl groups also include fused polycyclic aromatic ring systems in which a carbocyclic aromatic ring or heteroaryl ring is fused to one or more other heteroaryl rings. Examples include 2-benzothienyl, 3-benzothienyl, 2-benzofuranyl, 3-benzofuranyl, 2-indolyl, 3-indolyl, 2-quinolinyl, 3-quinolinyl, 2-benzothiazole, 2-benzooxazole, 2-benzimidazole, 2-quinolinyl, 3-quinolinyl, 1-isoquinolinyl, 3-quinolinyl, 1-isoindolyl and 3-isoindolyl.

Examples of suitable substituents on an alkyl, alkoxy, aryl or acyl group may include, for example, halogen (-Br, -Cl, -I and -F), $-OR_a$, -CN, $-NO_2$, $-N(R_a)_2$, $-COOR_a$, $-CON(R_a)_2$, $-SO_kR_a$ (k is 0, 1 or 2) and $-NH-C(=NH)-NH_2$. An alkyl group can also have =O or =S as a substituent. Each R_a is independently -H, an alkyl group, a substituted alkyl group, a benzyl group, a substituted benzyl group, an aryl group or a substituted aryl group. A substituted benzylic group or aryl group can also have an alkyl or substituted alkyl group as a substituent. A substituted alkyl group can also have a benzyl, substituted benzyl, aryl or substituted aryl group as a substituent. A substituted alkyl, substituted alkoxy, substituted aryl or substituted acyl group can have more than one substituent.

The following examples are not intended to be limiting in any way.

EXEMPLIFICATION

Example 1

Preparation of poly(2-*tert*-butyl-4-hydroxyanisole)

Horseradish peroxidase-catalyzed polymerization of 2-*tert*-butyl-4-hydroxyanisole (2-BHA) was carried out according to the procedure of Holland, H.L., in *Organic Synthesis with Oxidative Enzymes*, VCH Publishers, Inc., 1992, the contents of which are incorporated herein by reference. Briefly, 2-BHA (100 mg, 0.56 mmol) was added to a 1:1 (v/v, 6 mL) solution of methanol and 0.01 M sodium phosphate buffer (pH 7), along with horseradish peroxidase, at room temperature. The polymerization was initiated by incremental addition of a stoichiometric amount of hydrogen peroxide (5% aqueous solution, 35 microliters, 0.56 mmol) over a period of 3 hours. After complete addition of the hydrogen peroxide, the reaction was allowed to continue for another 24 hours. The solvent was evaporated by freeze-drying. The polymer was washed thoroughly with aqueous methanol (1:1 v/v) to remove the enzyme and phosphate salts, followed by drying under vacuum.

The 500 MHz ^{1}H NMR spectra of monomeric and polymeric 2-BHA are shown in Figs. 1 and 2, respectively. The NMR spectrum of the polymer shows clear changes from that of the monomer, such as the methoxy proton changing from a single peak at 3.7 ppm to a distribution of resonances between 3.4 and 3.8 ppm, which corresponds to the molecular weight of the polymer product. The distribution of molecular weights observed in the MALDI-TOF-MS spectrum (Fig. 3) also confirms formation of a polymer. A ^{13}C spectrum of poly(2-BHA) showed new peaks at 115.5, 116.2, 138.2 and 148.2 ppm, which suggests the presence of C-C and C-O-C couplings in the polymer (data not shown). Thermogravimetric analysis (TGA) profiles (Fig. 4) of 2-BHA showed there was about 15% mass loss up to about 125°C and TGA of poly(2-BHA) showed there was about 15% mass loss up to about 275°C, which indicates a considerable improvement in thermal stability for the polymer.

Example 2

Preparation of Poly(*tert*-butyl-hydroquinone)

Poly(*tert*-butyl-hydroquinone) was prepared by a variation of the method described in Example 1. The distribution of molecular weights observed in the MALDI-TOF-MS spectrum (Fig. 5) confirms formation of a polymer.

Example 3

Comparison of Antioxidant Activity of Monomers Versus Polymers

The antioxidant activity of monomers and enzymatically-prepared polymeric antioxidants was compared by measuring the bleaching of a beta-carotene system. In the model system, beta-carotene undergoes rapid discoloration in the absence of an antioxidant. The assay and measurements were conducted according to the procedure described in Jayaprakasha, G.K., *et al. Food Chemistry* 73: 285-290 (2001) and Hidalgo, M.E., *et al. Phytochemistry* 37: 1585-1587 (1994), the contents of which are incorporated herein by reference. Briefly, beta-carotene (0.2 mg), linoleic acid (20 mg), and 200 mg of Tween-40 (polyoxyethylene sorbitan monopalmitate) were dissolved in 0.5 mL of chloroform. The chloroform was removed under vacuum and the resulting mixture was immediately diluted with 10 mL of distilled water and mixed well for 1-2 minutes. The resulting emulsion was further made up to 50 mL with oxygenated water. Aliquots (4 mL) of the emulsion were mixed with 0.2 mL of test sample (monomer or polymer) in dimethylformamide (DMF), so that there were 100 ppm of monomer or polymer present in the aliquot. A control was prepared by mixing 0.2 mL of DMF with 4 mL of the above emulsion. The samples were incubated at 50°C. The absorbance of all samples at 470 nm was taken initially (t=0) and continued up to 180 minutes at 15

minute intervals. Data from the assay of 2-BHA and its polymer are shown in Fig. 6. Antioxidant activity is calculated based on the formula:

$$\text{Antioxidant Activity} = 100\,(1-(A_o-A_t)/(A^1{}_o-A^1{}_t)),$$

A_o = absorbance of the test sample at zero time,

$A^1{}_o$ = absorbance of the control at zero time,

A_t = absorbance of the test sample at time t (180 min), and

$A^1{}_t$ = absorbance of the control at time t (180 min).

The results for several monomer-polymer pairs are shown in the following table:

Compound	**Monomer Activity**	**Polymer Activity**	**% Increase in Polymer Activity**
2-*tert*-butyl-4-hydroxyanisole	44.24	53.74	21.5
tert-butyl-hydroquinone	5.77	9.7	68.1
4-azophenylphenol	5.4	25.5	372
phenol	2.1	10.0	376
3-hydroxybenzyl alcohol	1.0	5.0	400
4-methylphenol	0.9	5.0	455

Example 4

Antioxidant Activity of Monomer Versus Polymer

The antioxidant activity of several other antioxidant monomer/polymer pairs were determined by the procedure described in Example 3.

Compound	% Antioxidant Activity of Monomer	% Antioxidant Activity of Polymer
3-Hydroxybenzyl alcohol	1.0	5.0
4-Methylphenol	0.9	5.0
Phenol	2.1	10.0
4-Azophenylphenol	5.4	25.5

Example 5

Stability of Cooking Oils

Corn and canola oils were blended with amounts of *tert*-butyl-hydroquinone (TBHQ) and poly(TBHQ), such that the concentration of phenol moieties was equal. The oils were heated to frying temperature (190°C) and their oil stability index was measured. The oil stability index (American Oil Chemists' Society Cd 126-92) measures the amount of time before the oil begins to rapidly oxidize. A greater length of time indicates an oil with a greater antioxidant capacity, which likely corresponds to a longer potential shelf life.

Oil	Control	TBHQ	Poly(TBHQ)
Canola	7.8 hours	10.8 hours	19.2 hours
Corn	3.6 hours	6.6 hours	9.0 hours

The above table shows that polymerized TBHQ is more effective in preventing oxidation of the oils, as compared to monomeric TBHQ. Both TBHQ and poly(TBHQ) are significantly more stable than oil without an added antioxidant.

Example 6

Safety of Antioxidant Polymers

A study was conducted based upon the standards of OECD Guidelines for Testing of Chemicals, OECD 423. Ten Sprague-Dawley albino rats were administered with 2000 mg/kg body weight poly(TBHQ) as a single dose via gastric gavage. After administration, the animals were returned to their cages and observed for signs of toxicity for up to 14 days. Body weights were determined prior to dosing and on the day of death or prior to terminal sacrifice. A second study was performed using three female rats with 500 mg/kg body weight of poly(TBHQ).

Three of the five female rats administered with 2000 mg/kg poly(TBHQ) died prior to completion of the study. All animals manifested clinical signs of toxicity including piloerection, nasal discharge, chromodacryorrhea and lethargy. In the animals that did not survive 14 days, the intestines were inflamed. None of the surviving animals showed abnormal signs at gross necropsy. The three rats administered with 500 mg/kg poly(TBHQ) survived the duration of the study and did not manifest any clinical signs of toxicity.

Based on this study, the oral LD50 of poly(TBHQ) was determined to be between 500 mg/kg and 2000 mg/kg. For comparison, the oral LD50 of sodium chloride is about 3000 mg/kg and the oral LD50 of sodium cyanide is about 4 mg/kg. Thus, poly(TBHQ) has a relatively low toxicity to rats.

Example 7

Poly(2-*tert*-butyl-4-hydroxyanisole) Blends

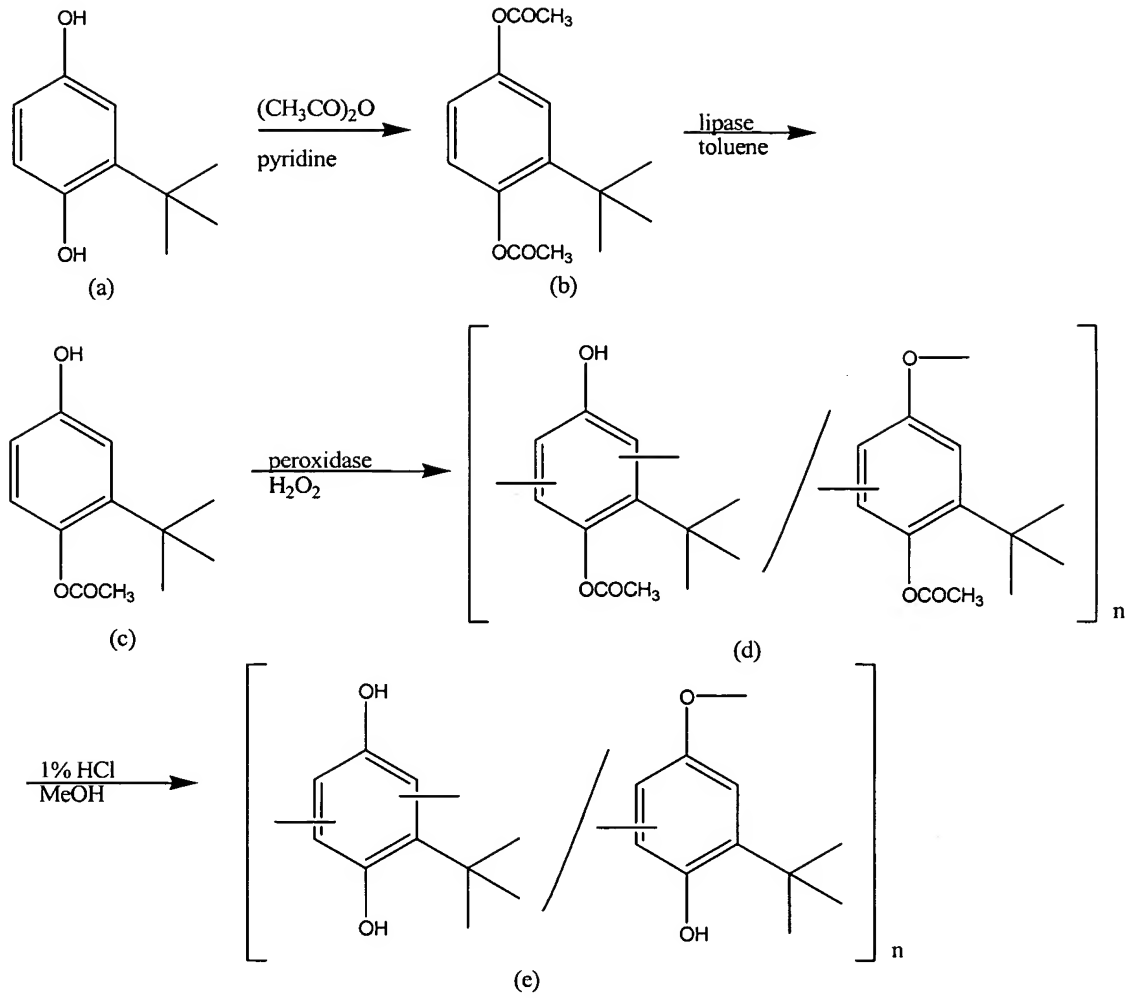
Extruding and film blowing methods were used to prepare polymer films containing a polymeric antioxidant. Powders or pellets of polyethylene or polypropylene were mixed with known proportions of 2-*tert*-butyl-4-hydroxyanisole (50 ppm), poly(2-*tert*-butyl-4-hydroxyanisole) (50 ppm) or a combination of the two

(25 ppm each). These mixtures were melted and extruded into pellets. The extruded pellets were then used to make blown films.

Example 8

Preparation of Poly(*tert*-butylhydroquinone)

The hydroxyl groups of *tert*-butylhydroquinone (TBHQ) were protected by reacting them with acetic anhydride in pyridine. The hydroxyl group distal to the *tert*-butyl group was then selectively deprotected by *Candida antarctica* lipase in toluene at 38°C, thereby forming 4-acetyloxy-3-*tert*-butylphenol. The 4-acetyloxy-3-*tert*-butylphenol was polymerized by horseradish peroxidase in the presence of hydrogen peroxide at pH 4.3. The protecting groups were then removed by treatment with 1% HCl in methanol. The reaction scheme is shown below:



The NMR spectra shown in Fig. 7 demonstrate that the desired product was formed at every step of the synthesis.

The antioxidant activity of compounds formed in each step of the scheme shown above were measured according to the procedure published in *Food Chemistry* 73: 285-290 (2001). The data are shown below; the lettering in the table refers to the compounds as labeled in the scheme above:

Compound	% Antioxidant Activity
a	6.72
b	2.45
c	7.9
d	9.43
e	18.86

The poly(TBHQ) was found to have about three-fold greater antioxidant activity than monomeric TBHQ. In addition, the antioxidant activity of poly(TBHQ) prepared by this method was about 77% greater (18.86% vs. 10.68%) than the antioxidant activity of poly(TBHQ) that was prepared without protecting and deprotecting the hydroxyl groups.

Example 9

Preparation of Poly(TBHQ)

Sodium phosphate buffer (0.01 M, pH=11, 6 liters) and dimethylformamide (DMF, 6 liters) were mixed together in a large container fitted with a mechanical stirrer. 200 g of *tert*-butylhydroquinone (TBHQ) was added to the mixture and the solution was stirred for 10 minutes. To this solution 3.9 g of hematin were added and the solution was stirred for an additional 30 minutes to ensure complete dissolution of hematin.

Hydrogen peroxide (1.2 moles, 25% aqueous solution) was prepared by dissolving 69 mL of hydrogen peroxide (50% solution in water) and 207 mL of deionized water.

Polymerization was initiated by the addition of 69 mL of the 25% hydrogen peroxide solution to the reaction mixture under vigorous stirring and three more additions of 69 mL of the 25% hydrogen peroxide solution were made at 15 minute intervals. After the four additions of hydrogen peroxide were complete, the reaction was stirred for additional 24 hours.

After completion of the reaction, the solvents (water and DMF) were removed and a brownish powder was obtained. The powder was dried and washed with a saturated solution of sodium bicarbonate many times to ensure removal of hematin. The powder was also washed with petroleum ether. The powder was further washed with water. The washed product was dried and weighed, giving a 50-55% yield.

This procedure was also conducted using a mixed solvent of isopropyl alcohol and water at pH 11.

EQUIVALENTS

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.